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Radio-tracking systems emit pulsed waves that could affect the health and alter the orientation of animals

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ABSTRACT

Any study carried out with a given technique must avoid causing harmful effects on the experimental subjects, in order to avoid altering the survival rates of the animals or causing bias in the results of the study. Radio tagging is undoubtedly a very useful technique, and in many cases is the only option available to obtain information on the ecology and movements of wild animals, but unfortunately it has been used indiscriminately, without regard to the problems it can cause. The most well-known of these are the effects from the weight of the device and the harness, but there are others that have not yet been taken into account and that have not been sufficiently studied, such as the non-thermal effects of modulated and/or pulsed electromagnetic fields on the health and orientation of radio-tracked animals. This commentary provides a brief overview of the scientific evidence on the effects of electromagnetic fields, and underlines the importance of carrying out relevant studies in order to check for the possible effects of radio transmitters on animals.

1. Introduction

Studies of the effects of tracking devices in terms of their weight and the accompanying harness have shown that birds may suffer several consequences from harnessed attachments, such as a loss of condition, weight reduction, increased risk of predation, infection, inflammation and negative effects on reproduction, such as embryo death/nest abandonment or failure and generally reduced investment in breeding (Geen et al., 2019; Kaplan, 2022).

Most radio-tracking systems rely on transmitters tuned to different frequencies, which allow for individual identification (Mech and Barber, 2002), and pulsed-wave transmission is the most commonly used mode for digital emitters (Balmori, 2016,2023). Radio transmitters produce radio frequency radiation with a RF carrier wave (range from 27 to 401 MHz) (Mech and Barber, 2002), and they are emitted in the form of on/off pulsations at extremely low-frequency (ELF) rates. The effects are dependent on power density/field strength, and the ELF pulsation and amplitude modulation of the electromagnetic fields (Balmori, 2023). Each pulse is approximately 0.02 s in duration, and the pulses are repeated continuously at a rate of 40 times per minute (Neill and Jansen, 2014). The pulse rate frequency set to 0.66 Hz (where less than 1 Hz is described as ultra low-frequency, ULF), meaning that these radio waves are even more bioactive than ELF (from 1 Hz to 300 Hz) pulsed waves (Panagopoulos et al., 2002, 2021; Panagopoulos and Balmori, 2017).

The non-thermal effects of pulsed radiofrequencies on the health of animals and people are well known (Balmori 2014, 2022a; Kostoff et al., 2020, Levitt et al., 2022a,b,c), and radio-tracking equipment can therefore have deleterious effects on the health of animals that carry it (Balmori, 2016,2023; Levitt et al., 2022a,b,c).

There are several different methods and types of radio-tracking devices used on animals. Very high frequency (VHS) attached devices are the most widely used variety, some of which have GPS capabilities. GPS geolocators that communicate with distant satellites may transmit data several times a day, depending on the setting. The average VHS radio transmitter fitted to wildlife produces a low-power radio pulse, but the location of the radiofrequency tagging attachment directly on an animal creates a strong body exposure, unless it is a device that transmits only when data are requested. If animals stay outside the optimal network coverage area (which frequently happens), when these GPS devices connect to satellites, connection and transmission will involve high power density radiofrequency exposures in close proximity to the animal at almost the peak power of about 2 W (ranges from about 250 mW to 2 W), roughly similar to a mobile phone (Fritz et al., 2020; Balmori, 2016, Balmori, 2022b).

In a previous review of studies that have shown effects on radio-marked animals, I argued that the long-term exposure of animals to man-made electro magnetic fields (EMFs) from GPS transmitters at non-thermal levels could explain the tissue damage and mortality found in

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such animals (Balmori, 2016). I also called for more systematic documentation and research on failures and any impairing effects on animals caused by such radio transmitters, in order to improve methods of animal monitoring (Balmori, 2023).

Although magnetic sensing and orientation have been used with a wide range of animal taxa, the specific mechanism by which animals orient themselves with the geomagnetic field has not yet been determined. The hypothesis that animals may sense geomagnetic fields through the existence of biogenic magnetite in their bodies, which could be reoriented by weak magnetic forces, is considered plausible (Kirschvink and Gould, 1981). It has also been hypothesised that certain photoreceptors may specialise in sensing the Earth's magnetic field in animals, acting via photo-signalling pathways initiated by the radical-pair mechanism (Ritz et al., 2004; Phillips et al., 2010). A mechanism in which varying polarised electric and/or magnetic fields initiate biological effects through ion forced-oscillation mechanism due to the dysfunction of voltage-gated ion channels is also an important theory (Panagopoulos et al., 2002, 2021; Panagopoulos and Balmori, 2017).

Current evidence indicates that exposure to low-level radiofrequency fields may particularly alter the magnetoreception process (Vacha et al., 2009; Wiltschko et al., 2014; Engels et al., 2014; Balmori, 2015). Radiofrequency fields in the MHz range disrupt the orientation of birds, as they interfere directly with the primary processes of magnetoreception and disable the avian compass as long as they are present (Wiltschko et al., 2014). Ritz et al. (2009) reported the sensitivity of the orientation of European robins (*Erithacus rubecula*) to radiofrequency magnetic fields. Robins are unable to use their magnetic compass in the presence of urban electromagnetic radiofrequency noise and the disruptive effect is not limited to a single narrow frequency range (Engels et al., 2014). Hence, radiofrequency radiation can affect the ability of some animals to orient themselves.

In the same way as for birds, man-made electromagnetic fields disrupt orientation in other vertebrates and invertebrates (Camlitepe et al., 2005; Balmori, 2015). The murine rodent compass is sensitive to low-level radiofrequency noise (100 MHz, ~ 1 nT) (Phillips et al., 2022). A low-level magnetic field (1.43 MHz at an intensity of 30–52 nT) has also been shown to disrupt the natural orientation of juvenile turtles (Landler et al., 2015; International Commission on the Biological Effects of Electromagnetic Fields 2022). The orientation of the American cockroach (*Periplaneta americana*) was found to be disturbed by weak pulsed radiofrequency fields at frequencies of 1.2 MHz, between 12 and 18 nT, and at 2.4 MHz, between 18 and 44nT (Vácha et al. 2009), and exposure to a frequency of 5 MHz of low level (~1 nT) alters the magnetic compass orientation in house flies (Phillips et al., 2022). There is a problem that each researcher uses different units for the electric or magnetic field that are not always easily comparable. However, the sensitivity of the orientation mechanisms have certainly a lower threshold than the emissions from radio transmitter (peak power of about 2 W at connection).

The use of radio-tracking devices has undoubtedly produced very important information in terms of knowledge of species, but it is essential to pay more attention to the possible problems associated with this approach. This paper will highlight the potential risks of using these devices to improve conservation management practises for birds and other species.

2. Problem

As mentioned in a previous paper (Balmori, 2016), laboratory scientists investigating the orientation of animals know there is a need to shield the place at which the experiments are performed, in order to prevent interference from man-made radiation, as anthropogenic signals may distort the results (Vacha et al., 2009; Wiltschko et al., 2014; Phillips et al., 2022; Muheim and Phillips, 2023). In the absence of such precautions (for example, filters covering a wide range of frequencies), the sensitivity to low-level radiofrequency fields at levels found in typical laboratory environments may be a source of unexplained variability when the spatial movements of animals are studied (Phillips et al., 2013; 2022). However, field scientists investigating animal movements and other aspects of animal ecology are equipping animals with radio transmitters that emit the same type of pulsed radiofrequency radiation (Mech and Barber, 2002).

The distortion effects on these wild animals in terms of their orientation and movements in nature may therefore be similar to those observed by scientists under laboratory conditions. This will occur even if the researchers do not have the opportunity to evaluate the effects of the radio transmitters, because the experiments were not designed to address potential disorientation effects caused by the tags (Balmori, 2016). However, it does not seem that researchers who use this technique even consider the possible existence of these effects and their ability to cause bias in the results of these studies, or the possible effects on the orientation and health of radio-tracked animals.

The problem may be that they are still influenced by the idea that electromagnetic radiation has only thermal effects (ICNIRP, 2020), although this view has been superseded and outdated for a long time (Bandara and Carpenter, 2018; International Commission on the Biological Effects of Electromagnetic Fields 2022; Balmori, 2022b). Plasma membrane calcium channels and other voltage-gated ion channels are irregularly activated/inactivated by man-made electromagnetic fields in animals, altering intracellular ion concentrations (Panagopoulos et al., 2021; Pall, 2016). Hence, any studies that neglect to consider electromagnetic fields as a variable in biological effects will overlook the well-documented biological interference effects of radiofrequency fields on cell integrity and function (Nyberg et al., 2022).

3. Examples

Due to its utility and versatility, and the lack of an alternative tracking method, thousands of studies have used radio tracking; however, the technique itself can interfere with the results of these studies (Balmori, 2016). An extreme example of this is provided by recent work by Karwinkel et al., (2022a,b). In order to explore the possible effects of magnetic pulses on their migratory traits, the authors exposed two species of birds, the northern wheatear (Oenanthe oenanthe) (Karwinkel et al., 2022a) and European robin (Erithacus rubecula) (Karwinkel et al., 2022b), to a magnetic pulser. Immediately after exposure, all birds in both the experimental (exposed to magnetic pulses) and the control group (sham treatment) were equipped with radio transmitters (NTQB-2, Lotek Wireless Inc) for radio tracking, and were then released. From a comparison of the exposed and control groups, the authors concluded that there was no apparent effect of the magnetic pulses (generated by the magnetic pulser) on the free-flight behaviour and migratory traits (departure probability, nocturnal departure timing, departure direction and consistency of flight direction). However, by their very nature, the radio transmitters used for bird tracking also produce pulsed radio frequency radiation, and hence both the experimental and the control group were exposed to electromagnetic pulses from the moment that the birds were equipped with radio transmitters.

Researchers participating in a reintroduction program for northern bald ibises (*Geronticus eremita*) documented the unilateral corneal opacity that was observed after the birds were equipped with solar radio transmitters (Fritz et al., 2020). The authors noted the fast recovery of the bird carrier after removal of the device; however, if the radio transmitter was allowed to remain, the corneal opacity advanced further and became irreversible. The ibis' habit of roosting with its head on its back suggests a plausible causal relationship between the placement of the GPS device (on the upper back) and this unilateral corneal opacity, since this roosting position brings one eye close to the radio transmitter. According to the authors, a cumulative proximity effect on the nearby eye during the roosting phase seems to be the cause of the disease. Although the authors propose several possible causes related to the device, such as contamination, chemical components, and persistent

slight mechanical irritation of the corneal stroma in the nearby eye during roosting, all of these potential mechanisms were discounted in the paper. Instead, the hypothesis that was put forth was a proximity effect from electromagnetic radiation transmitted by the GSM component in the range of radio waves, with peak power up to 2 W. The authors concluded that the probable explanation was a slight temperature rise in the corneal tissue due to electromagnetic radiation from the GSM module of the device (Fritz et al., 2020). However, these negative effects are not necessarily thermal, but may be non-thermal (Balmori 2022b).

The effects of the radiofrequency fields of radio-tracking devices could also explain some of the mortalities that have been observed, which do not have a convincing explanation to date. An important example is the reintroduction program of the red kite (*Milvus milvus*) in England (Peniche et al., 2011). Of 180 individuals recovered for post-mortem examination, 18 of these red kites carried a harness-mounted radio transmitter, of which four (22 %) had moderate to severe lesions, including chronic necrogranulomatous inflammation, deep muscular exposure and distorted muscular conformation. The authors blamed these problems on the harness and the presence of lesions was significantly associated with the length of time that the birds had carried the radio transmitters (from one month to seven years) (Dixon, 2011). However the authors did not consider the potential for long-term damage to be caused by radiofrequency fields of radio transmitters. The authors concluded: *"When considering the use of harness-mounted radio transmitters on birds in future, it will be important for the benefits, in terms of gathering useful information about the species, to be carefully balanced with the risks of adverse impacts on the birds. The use of harness-mounted radio transmitters should be closely monitored and further research to determine at what stage in the life of deployment the harnesses can become detrimental to the health of birds would be useful"* (Peniche et al., 2011). It is precisely the case that prolonged exposure to man-made electromagnetic fields has been found to weaken the immune systems of animals by altering various biological processes (Chou et al., 1992; Novoselova and Fesenko, 1998; Szmigielski, 2013). In addition, Levitt et al. (2022a) reported that deadly sarcomas were observed in the tissue around RFID chips imbedded in rodents and dogs (Albrecht, 2010), and severe metabolic changes were also observed in some animals implanted with RFID chips (Paik et al., 2016). Other recent studies have confirmed that mobile phone radiofrequency radiation can cause DNA damage and consequent carcinogenesis (Falcioni et al., 2018; Smith-Roe et al., 2020).

4. Conclusion and recommendations

Although radio tracking provides great advantages in terms of the study and monitoring of birds and other animals (Sokolov, 2011), it can be a harmful technology, since modulated and/or pulsed radiofrequency fields produce non-thermal effects (Balmori, 2014, 2015, 2023; Levitt et al., 2022a, b, c; International Commission on the Biological Effects of Electromagnetic Fields 2022). Of these, we can highlight the effects on the immune system, on behaviour and habitat use, decreased survival, increased mortality from neoplasia, effects on sperm quality and ovarian development, increases in embryonic mortality and miscarriage rates, biased sex ratios, and disturbances to magnetic compass orientation (Balmori, 2016). These non-thermal effects may explain some of the long-term impacts found in radio-tracked animals, such as lower annual survival rates, alterations in behaviour and activity, alterations in reproductive rates, biased sex ratios, or changes in movement patterns (Barron et al., 2010; Peniche et al., 2011; Balmori, 2016; Levitt et al., 2022a, b, c). Biologists should therefore reconsider the extensive use of these devices as if there were no consequences or confounding of the data collected from them.

There is no doubt that radio transmitters are very useful for understanding the migration patterns, behaviour, ecology and causes of mortality for many species, which can result informed conservation management practises for species. The detailed, high-volume data that can be obtained from these devices on species that are threatened and vulnerable to extinction are often critical to informing recovery plans; however, the benefits in terms of species conservation need to be weighed against the potential welfare impacts of device attachment, and the possible effects must certainly be taken into account (Balmori, 2016; Levitt et al., 2022a, b, c. These techniques must be used with care to prevent the possible effects they may have on species and their survivorship. If these technologies were not put into general use but were optimised instead, this could greatly improve studies and knowledge of species. A good solution might be the use of techniques or devices with lower impact or fewer harmful effects, e.g. devices that are connected only from time to time, and which transmit only when data are requested. It is imperative that commercial companies provide all relevant technical specifications to purchases (including frequency, pulse rate, power density/field strength, peak power…), in a manner that allows for comparisons across tags and systems, and this should be regulated in animal welfare legislation.

In order to establish whether data are skewed or outright misleading, it is essential to test this technology in comparative studies. One example is a comparative study of golden eagles undertaken a decade ago, in which one group were only ringed and the other were fitted with radio-tracking systems (McIntyre, 2012). This study showed that flight paths, distances travelled and survival rates were significantly different between ringed birds and radio-tracked ones, thus demonstrating convincingly that had the data been obtained solely by using telemetry, the results would be entirely misleading.

Radio-tracking devices are expensive, and sample sizes are typically small, making it complicated to conduct the robust comparative work required in this area. Conservation NGOs, government agencies who need animal movement data to support management and companies that sell these products should fund and conduct properly designed tests of these devices. An experimental approach to studying this aspect might involve the use of radio transmitters with different emission powers and variable frequencies, over different experimental periods, attached to wild birds in captivity, and may include animals exposed to radio-frequency radiation from radio-tracking devices with control groups (for example, this could be done with irrecoverable animals in rehabilitation centres). Studies in which simulated transmitters with similar loads, harnesses, sizes and shapes but without the radiofrequency pulse are mounted in the control group could help inform researchers as to whether these effects are in fact due to the pulsed radio signals. Given that the use of this technology is becoming ever increasing in field studies of avians and many other species, we urgently need to know more about the actual effects of the devices attached to animals.

Understanding the potential non-thermal effects of using radio-frequency systems can improve conservation management practises. This is because a greater understanding of these non-thermal effects, and how they can be mitigated, will reduce animal welfare impacts caused to species that carry these devices. The results from these studies will be very important for science, ornithology and conservation and presumably also for improving the welfare of animals studied.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Albrecht, K. (2010). Microchip-induced tumors in laboratory rodents and dogs: A review of the literature 1990–2006. *IEEE Int Symp Technol Soc*, 337–349.

Balmori, A. (2014). Electrosmog and species conservation. *Science of the Total Environment, 496*, 314–316.

Balmori, A. (2015). Anthropogenic radiofrequency electromagnetic fields as an emerging threat to wildlife orientation. *Science of the Total Environment, 518*, 58–60.

Balmori, A. (2016). Radiotelemetry and wildlife: Highlighting a gap in the knowledge on radiofrequency radiation effects. *Science of the Total Environment, 543*, 662–669.

Balmori, A. (2022a). a). Evidence for a health risk by RF on humans living around mobile phone base stations: From radiofrequency sickness to cancer. *Environmental Research, 113851*.

Balmori, A. (2022b). b). Corneal opacity in Northern Bald Ibises (*Geronticus eremita*) equipped with radio transmitters. *Electromagnetic Biology and Medicine, 41*, 174–176.

Balmori, A. (2023). Effects of man-made and especially Wireless Communication Electromagnetic Fields on Wildlife. In D. J. Panagopoulos (Ed.), *Electromagnetic Fields of Wireless Communications: Biological and Health Effects* (pp. 393–446). Taylor and Francis, Boca Raton, USA: CRC Press.

Bandara, P., & Carpenter, D.O. (2018). Planetary electromagnetic pollution: it is time to assess its impact. *The Lancet Planetary Health*, *2(12)*, e512-e514.

Barron, D. G., Brawn, J. D., & Weatherhead, P. J. (2010). Meta-analysis of transmitter effects on avian behaviour and ecology. *Methods in Ecology and Evolution, 1*, 180–187.

Camlitepe, Y., Aksoy, V., Uren, N., Yilmaz, A., & Becenen, I. (2005). An experimental analysis on the magnetic field sensitivity of the black-meadow ant Formica pratensis Retzius (Hymenoptera: Formicidae). *Acta Biologica Hungarica, 56*(3–4), 215–224.

Chou, C. K., Guy, A. W., Kunz, L. L., Johnson, R. B., Crowley, J. J., & Krupp, J. H. (1992). Long-term, low-level microwave irradiation of rats. *Bioelectromagnetics, 13*(6), 469–496.

Dixon, A. (2011). Effects of attaching telemetry equipment to free-living birds. *The Veterinary Record, 169*, 308–309.

Engels, S., Schneider, N. L., Lefeldt, N., Hein, C. M., Zapka, M., Michalik, A., et al. (2014). Anthropogenic electromagnetic noise disrupts magnetic compass orientation in a migratory bird. *Nature, 509*, 353.

Falcioni, L., Bua, L., Tibaldi, E., Lauriola, M., De Angelis, L., Gnudi, F., et al. (2018). Report of final results regarding brain and heart tumors in Sprague-Dawley rats exposed from prenatal life until natural death to mobile phone radiofrequency field representative of a 1.8 GHz GSM base station environmental emission. *Environmental research, 165*, 496–503.

Fritz, J., Eberhard, B., Esterer, C., Goenner, B., Trobe, D., Unsoeld, M., et al. (2020). Biologging is suspect to cause corneal opacity in two populations of wild living Northern Bald Ibises (*Geronticus eremita*). *Avian Research, 11*, 1–9.

Geen, G. R., Robinson, R. A., & Baillie, S. R. (2019). Effects of tracking devices on individual birds–A review of the evidence. *Journal of Avian Biology, 50*, e01823.

Icnirp. (2020). Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). *Health Physics, 118*(5), 483–524.

International Commission on the Biological Effects of Electromagnetic Fields (ICBE-EMF). (2022). Scientific evidence invalidates health assumptions underlying the FCC and ICNIRP exposure limit determinations for radiofrequency radiation: Implications for 5G. *Environmental Health, 21*, 92. https://doi.org/10.1186/s12940-022-00900-9

Kaplan, G. (2022). Casting the net widely for change in animal welfare: the plight of birds in zoos, ex situ conservation, and conservation fieldwork. *Animals*, *12*, 31. 10.3390/ ani12010031.

Karwinkel, T., Winklhofer, M., Christoph, P., Allenstein, D., Hüppop, O., Brust, V., et al. (2022). No apparent effect of a magnetic pulse on free-flight behaviour in northern wheatears (*Oenanthe oenanthe*) at a stopover site. *Journal of the Royal Society Interface, 19*(187), 20210805.

Karwinkel, T., Winklhofer, M., Janner, L. E., Brust, V., Hüppop, O., Bairlein, F., et al. (2022). Magnetic pulse does not affect free-flight navigation behaviour of a medium-distance songbird migrant in spring. *Journal of Experimental Biology, 225*(19), jeb244473.

Kirschvink, J. L., & Gould, J. L. (1981). Biogenic magnetite as a basis for magnetic field sensitivity in animals. *Bio Systems, 13*, 181–201.

Kostoff, R. N., Heroux, P., Aschner, M., & Tsatsakis, A. (2020). Adverse health effects of 5G mobile networking technology under real-life conditions. *Toxicology Letters, 323*, 35–40.

Landler, L., Painter, M.S., Youmans, P.W., Hopkins, W.A., & Phillips, J.B. (2015). Spontaneous magnetic alignment by yearling snapping turtles: rapid association of radio frequency dependent pattern of magnetic input with novel surroundings. PLoS One. 2015;10:e0124728. https:// doi. org/ 10. 1371/ journ al. pone. 01247 28.

Levitt, B. B., Lai, H. C., & Manville, A. M. (2022a). Effects of non-ionizing electromagnetic fields on flora and fauna, part 1. Rising ambient EMF levels in the environment. *Reviews on Environmental Health a, 37*, 81–122. https://doi.org/10.1515/reveh-2021-0026

Levitt, B. B., Lai, H. C., & Manville, A. M. (2022b). Effects of non-ionizing electromagnetic fields on flora and fauna, Part 2 impacts: How species interact with natural and man-made EMF". *Reviews on Environmental Health, 37*(3), 327–406. https://doi.org/10.1515/reveh-2021-0050

Levitt, B.B., Lai, H.C., & Manville, A.M. (2022 c). Low-level EMF effects on wildlife and plants: What research tells us about an ecosystem approach. *Front. Public Health* c, 10:1000840. doi: 10.3389/fpubh.2022.1000840.

McIntyre, C. L. (2012). Quantifying Sources of Mortality and Wintering Ranges of Golden Eagles from Interior Alaska Using Banding and Satellite Tracking. *J. Raptor Res., 46*, 129–134.

Mech, L.D., & Barber, S.M. (2002). A Critique of Wildlife Radio-tracking and Its Use in National Parks. Biological Resources Management Division, US National Park Service.

Muheim, R., & Phillips, J. B. (2023). Effects of low-level RF fields reveal complex pattern of magnetic input to the avian magnetic compass. *Scientific Reports, 13*(1). https://doi.org/10.1038/s41598-023-46547-5

Neill, E., & Jansen, P. (2014). Ground-based radio tracking: a best practice protocol. Department of Conservation, National Office, Wellington, New Zealand.

Novoselova, E. T., & Fesenko, E. E. (1998). Stimulation of production of tumor necrosis factor by murine macrophages when exposed in vio and in vitro to weak electromagnetic waves in the centimeter range. *Biofizika, 43*(6), 1132–1133.

Nyberg, N. R., McCredden, J. E., Weller, S. G., & Hardell, L. (2022). The European Union prioritises economics over health in the rollout of radiofrequency technologies. *Reviews on Environmental Health*. https://doi.org/10.1515/reveh-2022-0106

Paik, M. J., Kim, H. S., Lee, Y. S., Choi, H. D., Pack, J. K., Kim, N., et al. (2016). Metabolomic study of urinary polyamines in rat exposed to 915 MHz radiofrequency identification signal. *Amino Acids, 48*, 213–217.

Pall, M. (2016). Electromagnetic fields act similarly in plants as in animals: Probable activation of calcium channels via their voltage sensor. *Current Chemical Biology, 10* (1), 74–82.

Panagopoulos, D. J., Karabarbounis, A., & Margaritis, L. H. (2002). Mechanism for action of electromagnetic fields on cells. *Biochemical and Biophysical Research Communications, 298*, 95–102.

Panagopoulos, D. J., Karabarbounis, A., Yakymenko, I., & Chrousos, G. P. (2021). Human-made electromagnetic fields: Ion forced-oscillation and voltage-gated ion channel dysfunction, oxidative stress and DNA damage. *International Journal of Oncology, 59*(5), 1–16.

Panagopoulos, D. J., & Balmori, A. (2017). On the biophysical mechanism of sensing atmospheric discharges by living organisms. *Science of the Total Environment, 599*, 2026–2034.

Peniche, G., Vaughan-Higgins, R., Carter, I., Pocknell, A., Simpson, D., & Sainsbury, A. (2011). Long-term health effects of harness-mounted radio transmitters in red kites (*Milvus milvus*) in England. *The Veterinary Record, 169*, 311–316.

Phillips, J.B., Jorge, P.E., & Muheim, R. (2010). Light-dependent magnetic compass orientation in amphibians and insects: candidate receptors and candidate molecular mechanisms. *Journal of the Royal Society Interface, 7(suppl_2)*, S241-S256.

Phillips, J. B., Youmans, P. W., Muheim, R., Sloan, K. A., Landler, L., Painter, M. S., et al. (2013). Rapid learning of magnetic compass direction by C57BL/6 mice in a 4-armed 'plus' water maze. *PLoS One1, 8*(8), e73112.

Phillips, J., Muheim, R., Painter, M., Raines, J., Anderson, C., Landler, L., et al. (2022). Why is it so difficult to study magnetic compass orientation in murine rodents? *Journal of Comparative Physiology, A*, 1–16.

Ritz, T., Thalau, P., Phillips, J. B., Wiltschko, R., & Wiltschko, W. (2004). Resonance effects indicate a radical-pair mechanism for avian magnetic compass. *Nature, 429*, 177–180.

Ritz, T., Wiltschko, R., Hore, P. J., Rodgers, C. T., Stapput, K., Thalau, P., et al. (2009). Magnetic compass of birds is based on a molecule with optimal directional sensitivity. *Biophysical Journal, 96*, 3451–3457.

Smith-Roe, S. L., Wyde, M. E., Stout, M. D., Winters, J. W., Hobbs, C. A., Shepard, K. G., et al. (2020). Evaluation of the genotoxicity of cell phone radiofrequency radiation in male and female rats and mice following subchronic exposure. *Environmental and Molecular Mutagenesis, 61*(2), 276–290.

Szmigielski, S. (2013). Reaction of the immune system to low-level RF/MW exposures. *Science of the Total Environment, 454–455*, 393–400.

Sokolov, L. V. (2011). Modern telemetry: New possibilities in ornithology. *Biology Bulletin, 38*(9), 885–904.

Vacha, M., Půžová, T., & Kvíčalová, M. (2009). Radio frequency magnetic fields disrupt magnetoreception in American cockroach. *The Journal of Experimental Biology, 212*, 3473–3477.

Wiltschko, R., Thalau, P., Gehring, D., Nießner, C., Ritz, T., & Wiltschko, W. (2014). Magnetoreception in birds: The effect of radio-frequency fields. *Journal of the Royal Society, Interface, 12*, 20141103. https://doi.org/10.1098/rsif.2014.1103